

TOWARDS IN-FLIGHT QUALITY ASSESSMENT OF AIRBORNE LASER SCANNING

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ABSTRACT:

One of the main problems of today's ALS is the lack of reliable data quality assessment within or shortly after the airborne survey campaign. The paper presents an in-flight quality monitoring tool that allows assessing the quality of the recorded data "on the fly", featuring a real-time processing of the GPS/INS data and the subsequent georeferencing of the laser returns. The tool is capable of displaying the scanning progress in real-time and detecting data gaps immediately after terminating the strip. The paper presents the adopted strategy for data processing and communication in order to achieve scalable distribution across a network of computers. Further we discuss first experiences with this tool within airborne survey projects that demonstrate its successful application in practice.

1. INTRODUCTION

1.1 Motivation

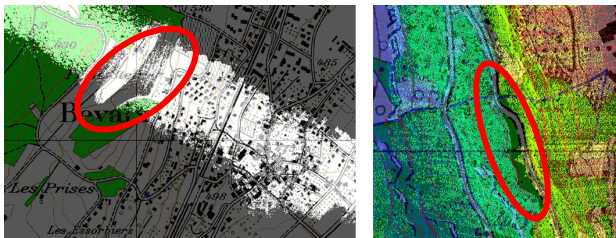


Figure 1: Insufficient data coverage detected in ALS point-cloud after post-processing due to poor reflectivity (left) or insufficient strip overlaps (right)

With measurement rates up to 167 KHz (Optech, 2008) Airborne Laser Scanning (ALS) provides masses of data. As a rule of thumb, it takes at least ten to fifteen hours to generate a final product for each hour of recorded information. Furthermore, as the costs per flight mission are considerable, it is essential to ensure that the area of interest is covered completely and the requirements, such as precision and point density, are satisfied. Although ALS has become well established and broadly used technology in the surveying industry, it is not uncommon to encounter pitfalls due to undetected sensor behaviour, varying data quality, consistency and coverage (e.g. Figure 1). These are only detected in post-processing, in other words, long after the flight. Worse, some types of errors can only be quantified by independent and expensive ground-based surveying methods. This may result in conditions where the data quality control may take an overwhelming part in the cost of a mapping product. Besides, the employment of such control further increases the time between a flying mission and the product delivery to a client. Therefore one of the main problems of today's ALS is the lack of reliable data quality assessment within or shortly after the airborne survey campaign.

The arguments raised above call for top-level of automation in data processing and a flexible in-flight quality monitoring tool that allows assessing the quality of the recorded data "on the fly" (Legat et al., 2006). The pre-requisite for such a tool is on one side the implementation of real-time (RT) processing of the GPS/INS data and the georeferencing of the laser returns; on the other side, the analysis of the trajectory integrity together with the scanning precision and geometry. This concept has already proven its feasibility in post-processing (Latypov, 2002; Schaer et al., 2007). This paper will focus on the implementation of such strategy in-flight in parallel with the data acquisition.



Figure 2: Handheld mapping system (Scan2map) installed in a helicopter

Our institution (EPFL-TOPO) lead the built up of a system called "Scan2map", that combines GPS, INS, ALS and a medium format digital camera in one solid mount (see Figure 2) (Skaloud et al., 2006). It can be used in nadir and oblique setup within the same flight. However, this flexibility in gaze direction as compared to classical ALS systems (i.e. fixed installation of the laser head on a plane), involves more accurate flight planning and tight control of plan execution to guarantee the complete data coverage. These particularities are also true for other ALS systems operated from helicopters and used for scanning projects in demanding topography at relatively low flying heights. Accordingly, the most important

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features for such an in-flight quality monitoring tool should be the RT display of the scanning progress and the detection data gaps within the flight.

1.2 Paper outline

We first present the strategy of merging the data streams from different technologies (i.e. inertial navigation, GPS positioning, laser range measurements) in real-time while performing all the necessary computations for obtaining the georeferenced laser point-cloud. Secondly, the core of the tool, the real-time GPS/INS orientation estimate and the subsequent RT georeferencing of the ALS data is presented in detail. Thirdly, we describe the qualitative evaluation of the strip data and its presentation to the system operator. Finally, we will present the results of first experiences and demonstrate its application in practice.

2. GENERAL SYSTEM ARCHITECTURE

Reaching in-flight data quality and coverage monitoring capacity required adopting a particular strategy in data processing and communication architecture that allows scalable distribution of tasks across a network of computers. The setup of data acquisition, synchronization and processing was guided by the following goals:

- Achieve independence between ‘vital’ and ‘extended’ system functionality
- Achieve performance scalability
- Achieve centralized monitoring and control

The first goal assures that the ‘vital’ modules responsible for data acquisition and synchronization cannot be disturbed by the state or processing requirements of the other modules. The second goal promises handling different scanning rates by means of separating modules individually (or in groups) across different computational platforms. Finally, the last goal centralizes the management for the flight operator.

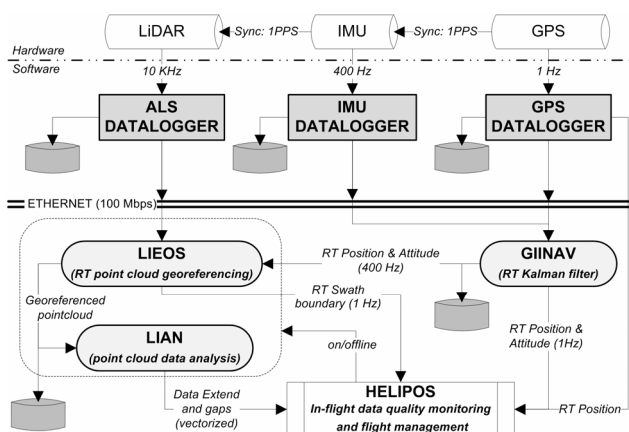


Figure 3: Overall architecture of in-flight quality tool

The fundamental prerequisite for achieving these goals is in establishing common and fast communication across all hardware and software components. The Ethernet with TCP/IP and UDP protocols has been chosen for this purpose. In the particular case of our mapping system, the Ethernet communication is already built-in in the LiDAR and IMU modules (Skaloud and Viret, 2004), while the GPS receiver needed to be interfaced to the network. The principles of the data acquisition and synchronization for this specific system were described in (Skaloud et al., 2006) and are schematically

outlined in the upper part of Figure 3. Practically, the timing scale is governed by the 1PPS and the timing offset is communicated between the modules via Ethernet.

As depicted in Figure 3, the LiDAR, the IMU and the GPS receiver have each its data acquisition software module. These modules can run on different processors if needed. Each module is responsible for storing the data and for passing them together with the status message to the connected clients. The control module (called HELIPOS in Figure 3) runs as a separate instance (usually on a different processor) and connects to all data acquisition modules in order to monitor their performance by means of status messages.

On the intermediate level there is firstly, the GPS/INS integration module ‘GIINAV’, secondly the direct georeferencing module (LIEOS) that embeds also the LiDAR analyses module (LIAN). These modules run again as independent instances that can be placed on different processors if needed. GIINAV connects to GPS and IMU data sockets and provides real-time GPS/INS navigation. Its position and orientation output is further broadcasted to LIEOS where it is merged with LiDAR raw measurements for

- real-time point-cloud generation within flight-line (see section 4)
- detailed point-cloud analyses (see section 5)

The outer bounds of the real-time laser profile generated by LIEOS are transmitted to HELIPOS that displays the scanning progress in the background of the flight plan (see Figure 8). HELIPOS can connect either to GIINAV for obtaining the current position, velocity and orientation data or to GPS data logger to obtain the receiver position and velocity from which the system-heading is calculated. After completion of a scan-line LIEOS calls the LIAN module to perform statistical testing on the obtained laser point-cloud and transmits this information to HELIPOS for visualization.

In the sequel we describe the system architecture in more detail from its intermediate level. Although we present a concrete system, the same architecture can be applied to different hardware by adapting only its bottom functionality, that is, the modules responsible for data acquisition.

3. RT GPS/INS INTEGRATION

The data processing applications (GIINAV and LIEOS) benefit from the same architecture. Both can be deployed either with graphical (e.g. Figure 4) and/or only shell interface (e.g. Figure 5). Alternatively, they can run silently in the background until receiving a termination message from the monitoring application (i.e. HELIPOS). Both applications can also initiate the bottom level programs from which they feed the data. Finally, their input/output is handled entirely via sockets. Therefore, they can be deployed across the network on different processors, if the system specific computation load requires so.

The navigation module GIINAV is the real-time strapdown inertial navigator and GPS/INS data integrator. The integration is performed via loosely-coupled Extended Kalman Filter (EKF) with 21error-state vector (Tome et al., 2000). The inertial data are processed in its original sampling (i.e. 400Hz in the actual configuration of the Scan2map), while the GPS data rate is typically set to one second. The critical part of the integration algorithm is related to its orientation initialization, a non-trivial issue especially for the helicopter-born flights. For that reason, the operator has the option to perform either

transfer, static or dynamic alignment. For maximum operation flexibility the static initialization can be constrained to a very short time if the approximate heading is specified using external information (i.e. magnetic reading). Nevertheless, the implemented modeling uses a customized version of the large-heading error model (Kong et al., 1999) and tolerates well larger initial uncertainties. Hence, it is possible to completely initialize or re-initialize the system in-flight without imposing much restriction on the dynamics (even for a helicopter).

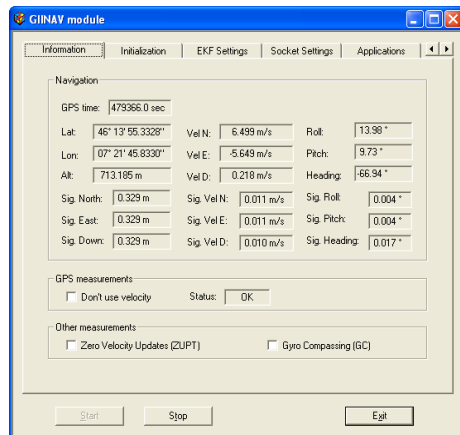


Figure 4: Information window of the GIINAV module graphical interface

The inertial navigation cannot completely monitor the integrity of GPS positioning, therefore different strategies are currently investigated to apply SBAS, RAIM and RTK technologies in a cascade form as suggested in (Skaloud, 2006). Hence, the real-time absolute positioning accuracy depends on the employed positioning mode (absolute, differential code and/or phase) and therefore ranges from meter to sub-decimeter level. The orientation accuracy is less dependent from the positioning mode and typically ranges from 0.01-0.03 degree in roll and pitch and 0.05-0.10 degree in heading when compared to the CP-DGPS/INS post-processed smoothed solution. A detailed evaluation the GIINAV performance is presented in section 7.

4. RT GEOREFERENCING (LIEOS)

The role of the georeferencing module is twofold: first, to generate the laser-point-cloud while on a flight-line, second to analyze its quality. The first task is a real-time operation handled by the LIEOS module, while the second is a delayed process handled by the LIAN (Lidar ANalyse) element. LIAN is not a standalone application but a separate thread of lower priorities that is entirely managed by LIEOS. Its functionality will be described separately in the following section.

The inputs to LIEOS are the LiDAR line data served by the ALS Data Logger (Figure 3) and the trajectory served by GIINAV, both at predefined data rates. On the output, LIEOS stores all laser point-cloud coordinates into a file and transmits points related to swath-characteristic (i.e., borders and nadir) to HELIPOS for displaying. LIEOS supports different projections and datum, choice of which is usually influenced by the datum and projection on the map used for pilot guidance.

```
15:41:41: Info: Start Georeferencing Points...
15:41:41: Info: ALS results file for line 1 successfully created...
15:41:44: GPS Time: 316766.318780, Line Count: 482
15:41:49: GPS Time: 316770.793300, Line Count: 502
15:41:54: GPS Time: 316775.401780, Line Count: 603
15:41:59: GPS Time: 316779.919850, Line Count: 703
15:42:04: GPS Time: 316784.393210, Line Count: 803
15:42:10: GPS Time: 316789.882490, Line Count: 904
15:42:15: GPS Time: 316793.521480, Line Count: 1004
15:42:18: Info: ALS results file for line 1 closed...
15:42:18: Info: End Georeferencing Points...
15:42:18: LIAN: Start new zone...
15:42:20: LIAN: Added 328055 points
15:42:22: LIAN: Analyse of line 1 terminated
```

Figure 5: LIEOS dos shell

The georeferencing algorithms implemented in the LIEOS were optimized to allow processing throughput of 'tens of thousands' points per second considering that the computational load per laser-return is influenced by several factors as: the frequency of trajectory output, the selected coordinate system, choice of the the georeferencing algorithm. These factors may vary per system or its setup (e.g., scanner rates may vary from 10 to 180 kHz, trajectory rates from 0.01 to 2 kHz) while the availability of processing power depends on the distribution of individual applications and the processor speed. Hence, to allow general use of this application, three georeferencing methods were implemented and their choice is left upon the user. These are:

- Fast (< 1 m),
- Approximate (< 1 cm),
- Rigorous.

The 'fast option' is an approximate method of sub-metric accuracy that is especially advantageous if the point-cloud is requested in the geographical coordinates. Despite its name, the 'approximate' method provides residual distortions at subcentimeter level only (in most flight scenarios) and regardless of the terrain characteristics (Legat, 2006; Skaloud and Legat, 2008). Its choice is especially advantageous, if a) the output is requested in national coordinates, b) the ratio scanner/trajectory sampling is relatively high. Finally, the 'rigorous' method is also optimized for speed, but uses no approximations. It performs the calculation of the laser point-cloud coordinates in a Cartesian system and then applies its rigorous transformation to the specified datum and projection. Although this method is more computationally demanding, its employment within the presented system requires no more than 10-15% of the total capability of the on-board processor.

5. LIDAR DATA ANALYSIS (LIAN)

As mentioned previously, LIAN runs as a separate thread within the LIEOS module. Its purpose is to analyze the quality and the completeness of the gathered laser data. The ALS data is only transmitted to LIAN once the actual flight-line is over. By pressing the offline/online button on the HELIPOS-GUI (see Figure 8), the operator communicates to LIEOS, if the system is

- Online: The raw laser data is stored; RT georeferencing is activated and swath boundaries are sent to HELIPOS
- Offline: No ALS data is stored; the georeferenced point-cloud of the previous flight-line is passed as one block to LIAN.

The temporal splitting of the two main tasks (i.e. the RT georeferencing vs. data analyze) allows keeping the CPU requirements at reasonable level.

Once the georeferenced point-cloud of a strip has been passed to LIAN, the program computes a density grid based on the 2D laser point coordinates (see Figure 6). The rasterized data coverage information is further processed to compute

- the complete data extend (outer bound of all strips within one flight zone) and

- b) the estimated data gaps (i.e. zones within the extend that were not scanned completely or haven't reached the minimal required point density).

After generalization of the boundaries using the Deuglas-Peucker algorithm (Douglas and Peucker, 1973), the vectorized boundaries are passed through socket to HELIPOS, where the controller can load the polygons in different layers and get an update of the actual data extend and zones with insufficient point density after each completed strip.

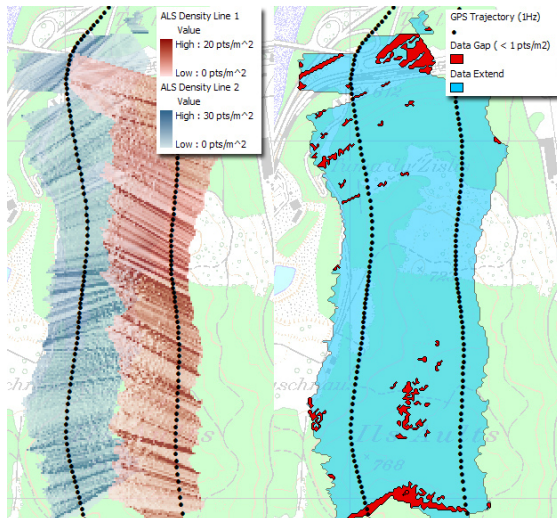


Figure 6: ALS density raster (left side) and vectorization of data extend and data gaps (right) for two parallel strips (Minimum Point density set to 1 point/m²)

The achievable accuracy of the LIAN analysis is in direct trade-off with the processing speed. Hence, in function of the project requirements and processing power the algorithm can be parameterized by:

- Minimum required point density in pts/m²
- Density raster resolution
- Vector generalization threshold
- ALS data thinning rate

The requirements on the computational effort can be specially lowered applying a “thinning” of input data to LIAN. Empirical tests have shown that reducing the ALS data up to one fifth of the initial laser points doesn't affect the quality of coverage analysis (extend and gaps) in LIAN.

6. IN-FLIGHT MISSION CONTROL (HELIPOS)

The control module is the graphical interface between the operator and the previously described modules. It has two major functions:

- 1) To provide flight management and guidance of the pilot
- 2) To control the system settings and to monitor the data quality and coverage

6.1 Flight management and pilot guidance

For the purpose of pilot guidance, HELIPOS offers two different views within the same instance (see Figure 7):

- The controller view, where all available information can be displayed (i.e. flight-lines, map data, RT position, RT swath, data extend and gaps)

- The pilot view, where only the map data, the actual flight-line and the current position and heading are displayed



Figure 7: Standard setup of HELIPOS in the cockpit: Controller view (bottom screen), pilot view as an extended screen on 8inch - monitor (top)

Setting up an extended screen on the controller laptop, the pilot view can be transmitted to an external screen (see Figure 7) through VGA connection. As both views run within the same application, they can be cross-linked. This enables the operator to control easily the pilots display by changing the view extend (e.g. zoom, pan) or by highlighting or deactivating the flight-lines.

6.2 System controlling and data quality monitoring

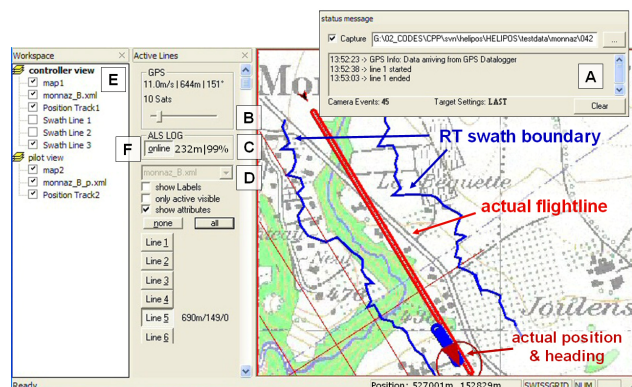


Figure 8: Overview of main functionalities of the HELIPOS graphical user interface (GUI)

Within a mission, all modules described until now run hidden form the user. HELIPOS is in charge of collecting all the necessary information and transmitting them to the system operator. Figure 8 depicts the most important controlling features:

- A. Status log: All important status messages from the data loggers (GPS/IMU/ALS) are gathered and listed in this window. Hence, data logging problems or identified hardware failures are communicated and the operator can react in consequence.
- B. GPS/INS info: The actual position, speed, heading and GPS quality indicators (e.g. DOP, number of visible satellites) can be displayed. When the GIINAV module is running, the operator has direct access to the integrated trajectory including RT attitude (roll, pitch and yaw) of the sensor head.
- C. ALS info: The measured distance by the laser and the swath coverage (in percent) can be displayed. This

improves the navigation for flight lines where a constant height over the topography is required.

- D. **Flight Plan management:** Different flight plans and flight lines can be loaded and activated. The line attributes (such as height, required speed over ground or sensor head attitude) can be displayed for each line.
- E. **Layer control:** GIS-like control to display or deactivate different data layers.
- F. **Online/offline button:** Control button to switch between online mode (RT georeferencing, display of RT swath boundary) and offline mode (data coverage analysis, transmission of data extend and data gaps to HELIPOS (see section 5)).

7. DISCUSSION OF RESULTS

The described software modules have been tested on several flights in the period of January to April 2008. In this section we will discuss some of the results comparing the real-time solutions (trajectory and raw point-cloud) and indicators to that of post-processing.

7.1 Trajectory

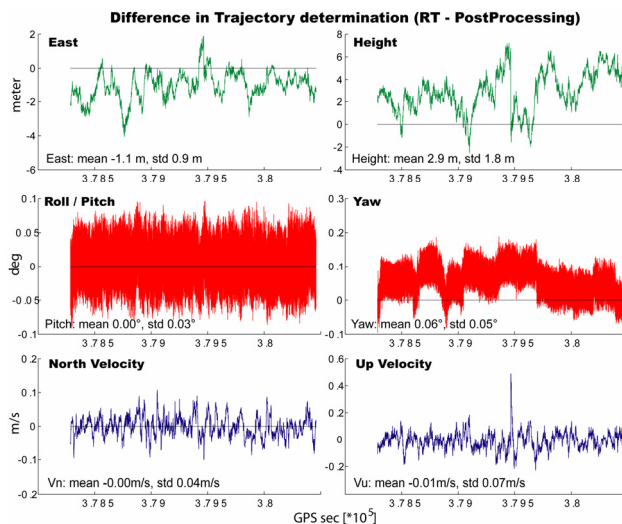


Figure 9: Difference in the computed position, attitude and velocity between the RT solution using point-positioning and post-processed solution using CP-DGPS.

Figure 9 shows the difference in trajectory estimation (position, attitude and velocity) between the RT solution using point-positioning (computed by GIINAV) and the post-processed results based on differential carrier-phase (computed by GrafNav/PosProc) for a flight by helicopter in the region of Lausanne (Switzerland). The plot depicts that the difference in attitude is low (roll /pitch: $\text{RMS} < 0.05^\circ$, yaw: $\text{RMS} < 0.1^\circ$) and close to the noise of the used IMU (Litton LN-200), whereas the difference in absolute position is more important ($\text{RMS planimetry} > 1.5\text{m}$, $\text{RMS altimetry} > 4\text{m}$). These results are not surprising, considering that neither DGPS nor RTK (Real-time Kinematics) were used for the RT solution. The correspondence in velocities is much better due to the influence of the IMU data.

7.2 Laser point-cloud

For the in-flight quality assessment of the ALS data mainly the accuracy and the completeness of the georeferenced point-cloud

is of interest. The histograms in Figure 10 depict the distribution of the point-cloud coordinate differences (RT point-positioning GPS/INS versus reference trajectory). As proven by forward covariance propagation (Glennie, 2006; Landtwing, 2005), the errors in position propagate directly into the georeferenced point. Accordingly, the east and north components are similar ($\text{RMS} \approx 1.5\text{ m}$) to the position errors in the trajectory (Figure 9). The RMS of the height component is about 2-3 times worse. But again, corresponds well to that of point-positioning accuracy in the vertical channel. In this particular flight the height over ground was approximately 250m. Thus, the angular discrepancies had a minor impact on the final georeferencing quality (roll/pitch: 0.05° at $250\text{m} \approx 0.2\text{ m}$). Hence, up to 1000 meters flying height a 2D point-cloud accuracy below 3m can be achieved without differential techniques. For the purposes of in-flight monitoring displaying the swath and the computation of data coverage, this accuracy is largely sufficient.

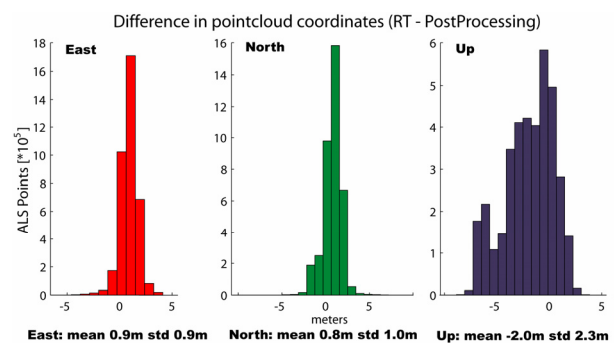


Figure 10: Histograms of difference in point-cloud coordinates computed in real-time and in post-processing (based on 3.7 Mio samples)

As the relative accuracy of the laser point-cloud is not affected by the positioning accuracy, the integrity of the results of LIAN can be guaranteed even in point-positioning mode. Comparing the data extends and data gaps computed using the RT and the post-processed point-cloud indicated no substantial differences. All data gaps were identified correctly, and the identified boundaries (in 2D) corresponded to the accuracy for the single laser point (i.e. $\text{RMS} \approx 1.5\text{ m}$).

7.3 System Performances

The testing in several survey missions was also very informative about the achievable system performances in terms of manageable data rates and CPU load. To separate the vital and extended elements physically from each other, the computing was divided on two field laptops:

- LOG-PC: linked to hardware (GPS/IMU/LiDAR) through Ethernet and running the GPS Datalogger, ALS Datalogger and IMU Datalogger modules.
- NAV-PC: Linked to LOG-PC through Ethernet and running the LIEOS, GIINAV and HELIPOS modules.

On the LOG-PC the CPU consumption was very low with peaks not passing 10%. Even tough data thinning of the raw ALS data can be enabled, we tested LIEOS at the full data rate of the employed laser (10'000 points/second). Trajectory computation by GIINAV was performed at 400 Hz, whereas trajectory information (position, attitude and velocity) was transmitted at 1Hz to HELIPOS. The swath boundaries were also updated at 1Hz. Running only the georeferencing and navigation modules occupied the CPU of the NAV-PC with less than 5%. The most

CPU demanding application is the visual GUI of HELIPOS with the map layer and the handling of different layers (e.g. flight-lines, system position, RT swath, data extend and data gaps). Especially performing zoom and pan operations (inducing complete screen refreshments) on the map loads the CPU up to 30%.

The performance analysis shows that the current configuration can manage and process the different data streams in real-time at full data rates. The whole application could even run on a single computer, although for safety reasons, a physical separation between the vital parts (data logging and storage) and extended functionality is recommended.

8. CONCLUSIONS AND OUTLOOK

While previous research focused on determining ALS data quality (i.e., the homogeneity, completeness and accuracy) by post-processing analyzes, in this contribution we proposed, designed and tested an approach that achieves good part of such evaluation in the real-time. By enabling such analyzes in the flight, the operator is immediately informed if part of the mission does not correspond to its requirements. From our experience, such information is critical in complex flight missions using helicopters and/or oblique orientation of the LiDAR sensor.

We presented modular software architecture where the data acquisition components are tied to a specific hardware while those related to data processing are not. The architecture is thus portable to different systems with the adaptation limited to the data acquisition components. If needed, the design is also scalable to different data throughput by running some modules on separate processors.

The empirical testing was limited to GPS data in point-positioning mode. Hence, the obtained accuracy of the real-time laser point-cloud reflected that of GPS and stayed at the metric level. Nevertheless, such accuracy proved to be largely sufficient to control the completeness of the scanning mission in terms of its coverage and density.

Our future efforts will focus on employing different strategies to improve RT positioning accuracy. These methods are of interest for controlling partially or completely the integrity of the GPS code and/or phase measurements before the post-processing. This information will be also pre-requisite for the extended quality analyses that incorporates rigorous error propagation considering all measurements, system components and laser incident angle as described in (Schaer et al., 2007).

9. ACKNOWLEDGMENT

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The GIINAV-Module is licensed software to EPFL by the third author.

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